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Spatial attention can be biased towards an expected dimension

RUNNING HEAD: Spatial attention and expected dimension

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Abstract

A commonly held view in both exogenous and endogenous orienting is that spatial attention is associated with enhanced processing of all stimuli at the attended location. However, we often search for a specific target at a particular location, so an observer should be able to jointly specify the target identity and expected location. Whether attention can bias dimension-specific processes at a particular location is not yet clear. We used a dual-task to examine the effects of endogenous spatial cues on the accuracy of perceptual judgments of different dimensions. Participants responded to a motion target and a colour target, presented at the same or different locations. We manipulated a central cue to predict the location of the motion or colour target. While overall performance in the two tasks was comparable, cueing effects were larger for the target whose location was predicted by the cue, implying that when attending a particular location, processing of the likely dimension was preferentially enhanced. Additionally, an asymmetry between the motion and colour tasks was seen; motion was modulated by attention and colour was not. We conclude that attention has some ability to select a dimension at a particular location, indicating integration of spatial and feature-based attention.

Keywords: *Spatial Attention, Feature-based Attention, Dual Task, Motion Processing, Colour Processing*

Spatial attention, as the name suggests, is based on the premise that attention selects based on location. Many studies have found faster and more accurate responses for targets in attended than unattended locations, reflecting this spatially-specific attentional bias (e.g., Berger, Henik, & Rafal, 2005; Carrasco, Ling, & Read, 2004; Cheal & Lyon, 1991; Jonides, 1980, 1981; Posner, 1980). Traditionally, the view was that when attention is oriented to a location, all dimensions at that location are selected (e.g. the spotlight theory Posner, Snyder, & Davidson, 1980; LaBerge, 1983; and the zoom lens model Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Müller, Bartelt, Donner, Villringer, & Brandt, 2003).

Conversely, feature-based attention selects specific features across the entire visual field, and therefore is not spatially selective (Sàenz, Buracas, & Boynton, 2002; Sàenz, Buracas, & Boynton, 2003; Serences & Boynton, 2007; White & Carrasco, 2011). This dichotomous view of attention implies that spatial and feature-based attention do not interact, but can only exert separate, additive effects (e.g., Egnér et al., 2008; Patzwahl & Treue, 2009; Treue & Martínez-Trujillo, 1999). However, there is evidence that feature-based attention and spatial attention may not operate in isolation. Research on contingent capture of attention found that under conditions in which participants must respond to a target, defined by a particular feature, only cues that share that feature will capture attention (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). Of particular interest is the finding that separate task sets can be maintained across different spatial locations (Adamo, Pun, & Ferber, 2010; Adamo, Pun, Pratt, & Ferber, 2008). For example, when observers were instructed to attend a blue target in the left visual field and a green target in the right visual field, exogenous cues which shared both colour and location of either target were more effective in attracting attention than other cues. The authors concluded that observers jointly specified the

location and color of potential targets, thus irrelevant conjunctions of location and colour were mostly disregarded. However, an alternative interpretation is that separate mechanisms may be used to specify the task relevant colour in the left and right visual field, and that spatial selectivity is simply a consequence of independent attentional resources for selection in the two hemifields (Alvarez & Cavanagh, 2001).

The finding that observers are able to pre-select specific features at a particular location suggests that spatial attention does not generalise across dimensions. A recent paper attempted to demonstrate the interaction of spatial and feature-based attention (Leonard, Balestreri, & Luck, 2015) by presenting RSVP streams in which participants identified a target defined by colour. Irrelevant distractors were presented at various distances from the RSVP stream. Distractors either matched or did not match the colour of the target. The closer the matching distractors were to the RSVP stream the greater the cost, whereas distance from the RSVP stream did not affect capture cost for the non-matching distractor. This finding strongly supports an interaction between spatial and features based attention, rather than their independence.

The above experiments did not manipulate the target dimension, such as motion or colour, but rather its selection feature. Remington and Folk (2001) examined the effects of exogenous spatial cues on discrimination of two separate dimensions. Participants were informed, trial by trial, whether to perform an orientation or a letter discrimination task. In both tasks the responses were mapped to the same two keys. Following the cue, tilted letters were presented at four locations: a red target, two white distractors which shared no features with the target, and a white foil, which shared either identity or tilt with the target. Thus, the responses evoked by the task relevant target dimension could be compatible or incompatible with the response evoked by either dimension of the foil. When the foil location was cued, only the task relevant

dimension showed a compatibility effect. This result suggests that at the cued foil location, only the dimension that is relevant to the task is attended. Interestingly, when the target location was cued, the task irrelevant dimension influenced response latencies. This suggests that both task relevant and task irrelevant target dimensions were selected.

While the effects described above must reflect top-down biases on visual selection, endogenous spatial cues have not been used to examine whether spatial deployments of attention can be feature and dimension selective. Therefore it is still unknown whether observers can modulate their attentional set to reflect faithfully the information provided by an endogenous cue.

The current study examines the attentional set following endogenous spatial cues. Participants performed two tasks simultaneously, which required detection and discrimination along two different visual dimensions, namely motion and colour. The motion and colour targets were preceded by a spatial cue, which was predictive of the location of one, but was uninformative as to the location of the other. We reasoned that if all task-relevant dimensions are selected at the cued location, then cueing benefits should be observed for both tasks, regardless of the dimension of the target whose location was cued. However, if the information provided by the cues is faithfully reflected in the attentional set, then a cueing effect should only be observed for the dimension whose location was predicted by the cue.

EXPERIMENT 1

The effect of a spatial probabilistic cue on a dual task was investigated using a dual task paradigm with two distinct stimuli and a single endogenous cue. In each trial, participants had to determine the direction of coherently moving dots and localise a red dot probe in one of four possible target locations. The cue was 70% valid for the location of one task, but was non-informative for the second task. We look at the validity effects for the two tasks, to see if there is a cueing benefit for the task for which the cue is uninformative. The validity effect is a commonly used index of the allocation of spatial attention (Jonides, 1981) as the difference in performance at the valid compared to the invalid location is representative of the difference in the usefulness of the cue. A larger validity effect for the task for which the cue is informative would show that attention was oriented in relation to the usefulness of the cue.

Method

Participants

Twenty-three naïve participants (17 female) from Bangor University were recruited through the online participant panel or via advert and were either awarded course credits or paid for their participation. All participants had normal or corrected-to-normal visual acuity. The Ethics Board of the School of Psychology, Bangor University approved both the experiments in this paper.

Stimuli & Apparatus

Stimuli were created using Matlab 7.6 with Psychophysics toolbox extensions (Brainard, 1997; Pelli, 1997) and generated by an Apple Mac Pro 1.1 computer. Stimuli were displayed on a LaCie Electron 22blue IV CRT screen, with a refresh rate of 60Hz. Head

position was restrained by a chin rest at a distance of 70cm from the monitor. The stimuli were shown against a black background, and participants were in a dark environment.

A pre-cue was used in each trial. The spatial cue was a 0.5° line, oriented towards one of the four quadrants of the screen. The neutral cue consisted of a colour change at fixation and provided only temporal information.

The stimuli were circular random-dot kinematograms (RDKs), of 10° diameter. Each RDK contained 100 randomly moving white dots, 0.2° in diameter. Each dot had a lifetime of three frames, with the location of its first frame determined by sampling a uniform distribution. The random movement, *dynamic noise*, was created by displacing the dot in a random direction within the aperture at a speed of $8.5^\circ/\text{s}$ on two consecutive frames.

In the motion-target RDK, the first 100ms of presentation was dynamic noise, followed by a 200ms period of *coherent motion*. During coherent motion, a certain proportion of the dots were displaced systematically on two consecutive frames in a given direction, either up, down, left or right, at the same speed ($8.5^\circ/\text{s}$) as the dynamic noise. The final 100ms of presentation was, again, a period of dynamic noise.

Simultaneously, a probe was presented on 50% of the trials. The probe was defined by a colour and size change of one of the RDK dots, which turned red and became slightly larger.

Design

Participants completed two blocks of 416 trials, on different, non-consecutive days. In one block the cue was informative for the location of the motion task, and in the other block, the cue was informative for the location of the probe task. In the motion cue

condition, on 70% of the trials the cue indicated the location of the coherent motion, while on the remaining 30% of the trials the coherent motion had an equal chance of being displayed at any of the uncued locations. In the probe cue condition, the cue information was reversed: On 70% of the trials the cue indicated the location of the red dot probe, if present, and on the remaining 30% the probe had an equal chance of being presented at any of the uncued locations, if present. The cues held no information about the location of the second task. Of the 416 experimental trials in each condition, 64 were neutrally cued trials. Neutrally- and spatially-cued trials were interleaved randomly.

Procedure

Participants were tested in two sessions on non-consecutive days; one session for each cue condition: The first session lasted two hours including training and the second session lasted one hour. Each participant completed 416 trials in each cue condition.

Firstly, participants practiced the tasks, with feedback, on a staircase procedure. No spatial information was provided during practice trials. The proportion of coherently moving dots and the size of the red dot probe were set at the level where participants were 60% accurate on the training trials. In the first session, participants completed 200 training trials on the motion coherence threshold program, and 200 training trials on the probe size program. In session one, participants were randomly allocated to begin with either the motion or probe cue condition.

When participants returned for their second session, they completed 80 trials each of the motion and probe training programs and difficulty levels were adjusted accordingly. They then completed the second experimental block, the opposite of the cueing condition they had completed in session one.

Figure 1 about here

The structure of each trial is displayed in Figure 1. A white marker, subtending 0.1° was visible at the centre of the screen throughout each trial. Eye movements were not recorded, but participants were told to maintain fixation on this point and that moving their eyes would make the tasks more difficult. At the beginning of each trial, the fixation marker was presented for 500ms, followed by a line (the endogenous cue) that was visible for 300ms. The target display appeared 200ms after cue offset, and lasted 400ms. Three RDKs contained dynamic noise and one also contained coherent motion. In 50% of trials a probe was presented for 100ms, and was equally likely to appear in any of the four locations. The probe appeared 150ms after target display onset.

At the end of each trial the participants were asked to indicate the direction of motion by selecting one of the four direction arrows. The following screen outlined the four locations and a central circle, and the participants selected the location where the probe had appeared, or in the case of an absent probe trial, the central circle.

Throughout this paper, participants were excluded from group analysis if they did not show a validity effect for the task for which the cue was useful. Our main interest was the attentional effect seen for the task for which the cue was not useful given that spatial attention was oriented to its location. In the experiments in which participants were excluded, this is clearly stated.

Results

Percentage accuracy was calculated for probe localisation by dividing the number of hits by the number of probe present trials in each condition. Motion accuracy was calculated across all trials. Six participants (six females) were excluded because the

cue failed to elicit a validity effect for the task for which it was reliable in one or both cueing conditions. The accuracies for the motion and probe tasks on valid and invalid trials are shown in Table 1, and the validity effects are plotted in Figure 2. These data are collapsed across the validity of the other task. For example, accuracy for trials in which the motion was presented at an invalid location includes trials in which the probe was presented at the valid location, at the same invalid location as the motion, or at a different invalid location. The data were normalised before group analysis, by taking the arcsine of the square root of the proportion of accurate responses, a standard transformation for proportional data, which normalises the data and stabilises the variance (Sokal & Rohlf, 1981).

Table 1 about here

Figure 2 about here

Results were analysed in a 2 (cue condition: motion, probe) x 2 (task: motion, probe) x 2 (validity: valid, invalid) repeated measures ANOVA. As expected due to the inclusion criteria, this yielded a significant validity effect, $F(1, 16) = 40.18, p < .001, \eta_p^2 = .72$. There was also a significant effect of task, as probe localisation was more accurate than motion discrimination, $F(1, 16) = 7.39, p = .013, \eta_p^2 = .25$. Crucially, there was a Cue Condition x Task x Validity interaction, $F(1, 16) = 10.71, p = .005, \eta_p^2 = .40$, suggesting that the validity effects for the two tasks was different following the two cues. The remaining comparisons were all non-significant ($F < 1$).

In order to examine this interaction, two separate ANOVAs were conducted for the two tasks (motion, probe), with cue condition (whether the cue was valid for the

location of the motion or the probe) and validity (valid, invalid) as factors. For the motion task, there was a significant interaction between cue condition and validity, $F(1, 16) = 12.92, p = .002, \eta_p^2 = .45$, suggesting that the magnitude of the validity effect was modulated by the usefulness of the cue. For the probe task, there was a significant validity effect, $F(1, 16) = 15.73, p = .001, \eta_p^2 = .50$, as valid trials were more accurate than invalid trials, indicating that the cue elicited an attentional effect. However, there was no interaction of cue condition with validity, $F(1, 16) = 1.81, p = .20, \eta_p^2 = .10$, suggesting that the validity effect was similar whether the cue indicated the likely location of the probe or not.

When comparing across the tasks, there is a modulation of the validity effect based on the task for which the cue is reliable. Therefore, using a spatial cue that is reliable for the location of only one target stimulus leads to biasing of attentional effects.

Discussion

The above experiment investigated whether spatial attention can be allocated by jointly using spatial and feature information in a cue, or necessarily generalises to all task-relevant stimuli at the cued location. It would not be necessary for the validity effects to be equal between tasks to make the case that attention generalises to both dimensions; here the interesting finding is the interaction: The magnitude of the validity effects within a task is modulated by the information in the cue. This finding challenges the assumption that spatial attention is a single entity that can be oriented or distributed, as proposed in previous models (Eriksen & Hoffman, 1973; Eriksen & St James, 1986; Eriksen & Yeh, 1985; Hoffman, 1979; Jonides, 1983; LaBerge, 1983;

Madden, 1992; Müller et al., 2003; Posner et al., 1980) and research (Egner et al., 2008; Fecteau et al., 2009; Patzwahl & Treue, 2009; Treue & Martínez-Trujillo, 1999).

The results support those of Remington and Folk (2001), who found that observers could restrict processing of attended stimuli to the task-relevant dimension, while ignoring the irrelevant dimensions. In our experiment, both dimensions were task-relevant, and a similar pattern was found: Cue information about the likely location of specific dimensions can be exploited when allocating attention. Processing is more enhanced at the cued location for stimuli whose location is predicted by the cue, in line with the findings of Leonard et al. (2015) that attention can restrict enhancement of target features to the spatial location in which the target will appear. This is consistent with the view that different task sets can be maintained for different locations (Adamo, Pun, Pratt, & Ferber, 2008; Adamo, Pun, & Ferber, 2010).

It is proposed that attention affects motion and colour processing differently at the cued location, based on the reliability of the cue for the given dimension differences between the two tasks used above in order to make the demands more similar and increase the number of trials used for analysis. Firstly, in Experiment 1 the motion task required discrimination and the colour task required detection and localisation of a stimulus that was only present 50% of the time; these tasks may affect higher-order attentional processes differently. Moreover, the spatial extent of the target stimuli were different: The motion task filled the entire RDK window and would be best completed by integrating local motion signals, whereas the probe task required detecting a single red dot, and integration of signals would hamper performance in this task. Therefore, rather than biasing attention by colour or motion, there may have been differences between the stimuli that led to strategic differences in how the tasks were completed. A third difference between the tasks is that the red dot probe was never a coherently moving

dot. This may have meant that the stimuli were interpreted as distinct objects (Duncan, 1984; Egly, Driver, & Rafal 1994), and that the difference in validity effects was due to attention being oriented to one of these 'objects'. These potential confounds are addressed and discussed in the following experiment.

EXPERIMENT 2

Experiment 2 is a variant of the dual-task set up in Experiment 1 in which one task was reliably cued. The same motion discrimination task was used, while the colour task was a colour change of a proportion of RDK dots, and participants reported whether the dots changed to red or green, such that both tasks span an entire RDK and both require discrimination.

Method

Participants

Twenty-seven naïve participants (20 female) from Bangor University were recruited via advertisement and compensated for their time, or through the online participant panel and awarded course credits for their participation. All had normal or corrected to normal vision. None had taken part in the previous cueing experiment.

Stimuli & Apparatus

Stimuli were created as in the previous experiment with the following changes: All the dots were orange and instead of a colour probe, in one of the four RDKs, the dots changed to either red or green for 100ms. An equiluminance procedure was run to find the subjective ratio for green compared to red for each participant. Following this, in the training and the experiment, red was set at [255 0 0] and green set as the equiluminant

[0 (255*ratio from the equiluminance program) 0]. Following piloting, these colours were then mixed slightly (80% of the original colour with 20% of the opposing colour) to increase difficulty of the discrimination task. Mixing the red and green RGB values together created the orange shade that was equal in luminance to both the red and the green and was the colour of all dots other than the red or green colour discrimination dots.

The number of motion and colour discrimination dots was determined using staircase coherence programs. The threshold at which participants were 60% correct at the discrimination task was selected for use in the experiment. Colour change dots were selected from the RDK dots independently of the coherent motion dots, so that if both tasks appeared at the same location, colour change dots included both translating dots and randomly moving dots. Similarly, coherently moving dots contained both orange and colour change dots.

Design

In the motion cue condition, on 70% of the trials the cue indicated the location of the coherent motion, while on the remaining 30% of the trials the coherent motion had an equal chance of being displayed at any of the uncued locations. Conversely, in the colour cue condition, on 70% of the trials the cue indicated the location of the colour change, while on the remaining 30% of the trials the colour change was equally likely at any of the uncued locations. Sixty-four of the 416 trials in each condition were neutral trials. Accuracy in discriminating the direction of coherent motion and colour change were measured.

Procedure

Participants were tested in two sessions on non-consecutive days; one session for each cue condition. The first session lasted two hours including training and 416 experimental trials, and the second session lasted one hour. Participants first completed an equiluminance procedure, in which a freely-available script was modified, based on the minimum motion luminance measurement procedure (Cavanagh, MacLeod, & Anstis, 1987). Briefly, the stimulus consisted of a complex, annular grating comprising two counter-flickering, superimposed visual patterns. When the two components were superimposed, the annulus appeared to rotate either clockwise or anti-clockwise unless the luminance of the two phosphors was matched. Participants reported the direction of motion as clockwise or anticlockwise, and responses were used to compute a cumulative probability function. The ratio of red to green luminance at which participants were equally likely to report clockwise and anticlockwise motion was the point of equiluminance. In the first block of trials, well-spaced luminance ratios were used. Subsequent blocks used decreasing increments of luminance values to focus in on the equiluminance point.

Participants then completed motion coherence and colour discrimination training programs, both on staircase procedures with no spatial cue. The training programs were used to set the number of dots for motion discrimination and colour discrimination in the experiment, at the level at which participants were 60% correct.

The structure of each trial was the same as that of the previous experiment. The participants were aware that the colour change dots were equally likely to be red or green. Participants were instructed to report both the direction of coherent motion and the colour of the dots at the end of each trial.

When participants returned for their second session, they completed 80 trials each of the motion and colour training programs and thresholds were adjusted

accordingly. The same equiluminance value was used as in session one. They then completed the second experimental block in the other cueing condition.

Results

Three participants were excluded, because they failed to show a validity effect for the reliably cued task in both cue conditions. Accuracies for both tasks on valid and invalid trials are shown in Table 2.

Table 2 about here

Figure 3 about here

Validity effects

Figure 3 shows the validity effects for each task. Results were analysed in a 2 (cue condition: motion, colour) x 2 (task: motion, colour) x 2 (validity: valid, invalid) repeated measures ANOVA. There was a significant validity effect, $F(1,23) = 79.72, p < .001, \eta_p^2 = .78$, as expected. There was also a Task x Validity interaction, $F(1,23) = 10.61, p = .003, \eta_p^2 = .32$ and a Cue Condition x Validity interaction, $F(1,23) = 5.56, p = .027, \eta_p^2 = .20$, driven by the larger validity effect for motion when motion was cued. Importantly, there was a significant Cue Condition x Task x Validity interaction, $F(1,23) = 5.09, p = .034, \eta_p^2 = .18$. All further comparisons were non-significant ($F < 1$).

A 2 (cue condition: motion, colour) x 2 (validity: valid, invalid) repeated measures ANOVA was conducted for each task to examine the three-way interaction. For the motion task, there was a main effect of validity, $F(1,23) = 77.08, p < .001, \eta_p^2 = .77$. The Cue Condition x Validity interaction was also significant, $F(1,23) = 7.77, p = .010, \eta_p^2 = .25$, suggesting that the validity effects in the motion task depended on whether the

cue was useful for the task. For the colour task, there was a main effect of validity, $F(1,23) = 33.36, p < .001, \eta_p^2 = .59$, but no Cue Condition x Validity interaction, $F < 1$.

Thus, the overall findings in Experiment 2 show a similar pattern to Experiment 1 and suggest that spatial attention can be biased by information on the expected location of a particular dimension.

Location effects

We ran two further analyses designed to examine effects for the two tasks when they occurred at the same or different locations. The first was to compare the cueing effects when both tasks were at the same location i.e. trials in which both tasks appeared at the valid location or both tasks appeared at the same invalid location. These trials were analysed in a 2 (cue condition: motion, colour) x 2 (task: motion, colour) x 2 (validity: valid, invalid) repeated measures ANOVA. There was a significant validity effect, $F(1,23) = 29.56, p < .001, \eta_p^2 = .56$, and a Task x Validity interaction, $F(1,23) = 4.43, p = .046, \eta_p^2 = .16$, similar to the results when using all the trials. The Cue Condition x Validity interaction did not reach significance here, $F(1,23) = 2.99, p = .097, \eta_p^2 = .12$. Importantly, the Cue Condition x Task x Validity interaction, $F(1,23) = 11.36, p = .003, \eta_p^2 = .33$ remained significant. As in the previous analyses, a 2 (cue condition: motion, colour) x 2 (validity: valid, invalid) repeated measures ANOVA was conducted for each task to examine the three-way interaction. For the motion task, there was a main effect of validity, $F(1,23) = 26.35, p < .001, \eta_p^2 = .53$, and a Cue Condition x Validity interaction, $F(1,23) = 13.01, p = .001, \eta_p^2 = .36$. For the colour task, there was a main effect of validity, $F(1,23) = 10.30, p = .004, \eta_p^2 = .31$, but no Cue Condition x Validity interaction. This pattern mirrors the pattern we saw when we included all trials.

We ran a second analysis on the trials in which both tasks appeared at invalid locations, in a 2 (cue condition: motion, colour) x 2 (task: motion, colour) x 2 (location: same, different) repeated measures ANOVA. Only the main effect of location was significant, $F(1,23) = 9.73$, $p = .005$, $\eta_p^2 = .30$. The results show that stimuli sharing a location resulted in higher accuracy than stimuli in different locations, as can be seen in Table 3. The effect was not different for the two tasks or the two cue conditions; it is an overall benefit.

Discussion

The pattern of results from Experiment 1 is mirrored here with a different colour task which required discrimination of threshold stimuli. If the results in Experiment 1 were due to differences in task demands (discrimination versus detection), the validity effects for the two tasks in Experiment 2 should have been comparable in the two cue conditions. However, the validity effects were modulated based on the information in the cue, suggesting that the effects are due to differences in allocation of attention to dimensions.

A second difference between the motion and probe in Experiment 1 was that the two tasks were of different sizes; the coherent motion filled the entire RDK, but the probe was a single red dot. In Experiment 2, both tasks were represented across the RDK and there was still a larger cueing benefit for the motion task than the colour task when the cue was predictive for the location of the motion, hence it is unlikely that the attentional modulation was due to the spatial extent of the task.

Last, in Experiment 1, when the colour task was a single red dot probe, it was always one of the non-coherently moving dots and there is a possibility that they may have been perceived as distinct objects. Proponents of object-based attention report that

attention generalises across all features of an object once it has been selected (Duncan, 1984; Egly, Driver, & Rafal, 1994). The colour change dots in Experiment 2, however, were drawn from both coherently moving and non-coherently moving dots when both tasks appeared at the same location. Thus, though the present experiment was not designed specifically to examine an object-based explanation, we make the assumption the motion and colour discrimination tasks were completed on the same object. The results show the pattern expected if participants are able to bias spatial attention towards a likely dimension at the cued location.

The additional analyses presented for Experiment 2 provide a fuller appreciation of the data than the previous experiment. We show that even on trials on which both tasks appeared at the same location, the information in the cue modulates the pattern of validity effects. This pattern mirrors the pattern we saw when we included all trials, suggesting that the validity effect results are not driven by trials on which tasks appeared at different locations. On these trials, participants were required to divide attention and may therefore have prioritised the task for which the cue was informative. For example, the validity effects for the colour task for the two cue conditions are comparable, and this pattern remains when examining trials on which the motion appears at the same location as the colour. This suggests that the results do not reflect prioritising the motion task when the cue is relevant for the motion location, else we would have seen a smaller effect when attention was not divided.

Next, we examined what happens when the tasks appeared at the same or different invalidly cued locations. We found that there was a benefit for both tasks when they shared a location compared with when they appeared at different locations, but that this benefit did not interact with the cue condition. This is interesting because it suggests that our effects are driven by what happens at the cued location.

General Discussion

The current study was designed to investigate whether following an endogenous spatial cue attention enhances all task-relevant stimuli at the cued location, or whether information provided by the cue can be faithfully represented to allocate attention. When a spatial cue was only predictive for the location of one stimulus, that stimulus showed a larger validity effect compared to when the cue was not predictive for its location. Therefore, the major outcome from our experiments is that spatial attention can be allocated differently, through attentional sets, based on the information provided by the cue. The second outcome from our experiments is the finding that motion and colour stimuli show an asymmetry in attentional effects: The validity effect for motion was modulated by cue information, but the validity effect for colour was not. These conclusions will be discussed in turn.

Spatial attention does not enhance all stimuli at the cued location equally

In the current study we presented two stimuli that both required a response; a motion task and a colour task. While the cue was predictive of the location of one stimulus, it was uninformative as to the location of the second. We observed a larger validity effect for the task for which the cue was useful than the task for which the cue was not useful. This was the case both when the tasks were dissimilar (Experiment 1) and when they were similar (Experiment 2), and remained when both tasks appeared at the same location. Rather than simply directing spatial attention to a particular location at which all dimensions are attended, we suggest that attention can bias towards likely dimensions at the cued location.

Previous research is consistent with the view that spatial attention does not generalise equally to all dimensions at the cued location. Leonard et al. (2015) showed that the spatial proximity of a distractor to a target in an RSVP stream affected capture cost only when the distractor shared a feature with the target. This suggests that spatial attention can selectively enhance features, in a top-down fashion. Using exogenous spatial cues, Remington and Folk (2001) found that observers could restrict processing at attended locations to the task-relevant dimension, while ignoring the task-irrelevant dimensions. In our experiments, we used endogenous spatial cues and both dimensions were task-relevant, yet we do not find that spatial attention affects both equally. Rather, we find that processing of task-relevant dimensions is more enhanced at the cued location for the dimension whose location is predicted by the cue than for the dimension for which the cue was uninformative.

Functional imaging work (Jehee, Brady, & Tong, 2011) has provided initial physiological evidence that the effects of spatial attention do not necessarily enhance all dimensions at the cued location. Two tilted Gabor stimuli were presented either side of a central fixation point, and a spatial cue informed participants of which Gabor to attend. Participants performed either an orientation, contrast, or colour task at the attended location. Therefore, participants were attending a particular feature at one location in the visual field. Voxel-wise patterns of the visually-evoked BOLD response were shown to be informative of the attended target's feature only when the feature belonged to a task-relevant dimension. For example, when participants performed an orientation discrimination task, the orientation decoding accuracy was higher for the attended location than the unattended location. However, when performing a contrast discrimination task, the orientation decoding accuracy was no different at attended and unattended locations. In other words, the effects of spatial attention did not generalise

to task-irrelevant dimensions. As our behavioural results show that attention can be biased towards likely dimensions at the cued location, the effects of attention on visual cortical areas may provide the foundation for selection based on both likely location and dimension.

Asymmetric effects for motion and colour

Though we find compelling evidence that participants are able to exploit specific cue information, we observed an asymmetry. The validity effect for the motion task was modulated by the usefulness of the cue, whereas the validity effect for the colour task was equal regardless of the cue condition. This asymmetry suggests a larger role for attention in motion processing than colour processing. Supporting evidence for this account comes from examination of visual processing pathways in the brain, from imaging investigations of higher-order attentional mechanisms, and can possibly be explained by central resource allocation.

It has been suggested that though the effects of attentional orienting are evident in both the ventral and dorsal streams (Ungerleider & Haxby, 1994; Ungerleider & Mishkin, 1982), the dorsal stream is more heavily involved in directing attention (Itti & Koch, 2001). As the dorsal stream is also concerned with motion processing (Ungerleider & Haxby, 1994; Ungerleider & Mishkin, 1982) this relationship could explain the larger attentional effects on motion stimuli than colour stimuli in our experiments. Higher order attention regions have also been studied with regards to stimulus properties. When attending to either motion or colour in random dot patterns, larger, more extensive activation has been found following motion than colour cues (Liu, Slotnick, Serences, & Yantis, 2003; Shulman, d'Avossa, Tansy, & Corbetta, 2002). Hence, there is seemingly a bias in higher order attentional regions for motion over colour. This

suggests that motion may be prioritised in attentional processing such that motion is modulated to a greater degree. Our results may, therefore, reflect the priority of motion in attention, as the validity effect for the motion task was modulated as a result of attention. Additionally, the validity effect for the motion task was larger than for the colour task.

In our design, it is not clear which stage of processing is responsible for these asymmetrical results. We propose that the effects are driven by early processes because we interpret these results in differences in allocation of attention. However, we cannot reject the possibility that later processes on response selection caused the asymmetry. Indeed, Lachter, Remington, and Ruthruff (2009) showed that no matter which response is prepared for, only the executed response shows dimensional selectivity. Though in our experiment, participants executed both responses, they prepared the response to the motion task before the response to the colour task. This could explain why the motion was modulated by the cue while the colour task was not.

The interaction of spatial and feature-based attention

The finding that spatial attention can be biased towards particular dimensions (and features, Leonard et al., 2015) has implications for the relationship of spatial and feature-based attention. Our results suggest that the location and the dimension of a visual target can be jointly selected by attention. This is consistent with the known organisation of visual cortex, in which areas specialised for processing dimensions such as motion and colour are organised according to retinal locations. However, the suggestion that attention can be biased towards the likely dimension at a spatially cued location is at odds with a large body of empirical evidence which supports the idea that spatial and feature-based attention are distinct mechanisms. More specifically, previous

research suggested that spatial attention generalises across non-spatial dimensions, while the effects of feature attention are spatially non-selective (e.g. Sàenz et al., 2002, 2003). Additionally, others have reported that the effects of spatial and feature cueing, on physiological measures of neural activity, are additive (e.g., Egner et al., 2008). However, optimal performance in this study required that spatial and feature cues be utilised independently, and therefore the effects could reflect either the task demands or the organisation of attention. There are circumstances, as in our study, in which optimal performance requires the integration of spatial and non-spatial information for selection. Since the results indicate that not all stimuli at the cued location show equally-improved visual processing, we suggest that spatial attention and feature-based attention can interact. Interestingly, people have argued that the conjunction of spatial and feature-based attention happens at a later processing stage (Adamo et al., 2010).

We propose that spatial attention can be biased at the cued location for the dimension for which the cue is useful. There are two possible theoretical explanations for this result. One way to think about this argument is that participants can maintain two parallel task sets (e.g. Adamo et al., 2008), one for motion and one for colour. This is an intuitive separation given that motion and colour are processed in separated visual streams. For each task set, participants are able to allocate attention based on a different spatial profile; that is, focused attention for the task related to the cue and distributed attention for the task for which the cue is not useful. In the context of these previous results on task set, we illustrate here that participants are able to use an endogenous cue to flexibly allocate attention – possibly in divided task sets – on a trial-by-trial basis.

Interestingly, when looking at trials on which both tasks appeared at the same invalidly cued location, we saw no bias towards the task for which the cue was informative. This presents an alternative theoretical explanation that a conjunction of

spatial and feature-based attention is first allocated to the cued location, and when the target is not there, attention is then reoriented. Our results suggest that once attention has been reoriented from the cued location, the bias towards the dimension for which the cue is informative is no longer present; we search for all relevant targets in the knowledge that they are equally likely to be at any uncued location. Thus we are able to faithfully utilise the information in the cue.

In summary, the results demonstrate that spatial attention can be biased by prior information regarding the stimulus likely to appear in the cued location, reflecting an interaction between spatial and feature-based attention. Top-down attentional mechanisms can exploit visual organisation and employ joint selection of stimuli based on spatial and dimension information. Furthermore, the effects of attention depend on the dimension: Whereas the validity effect was modulated for a motion target, colour processing did not show the same effect. This is consistent with a view of motion as prioritised in attention networks. We present two explanations that may account for our results: the maintenance of two parallel task sets, or a reorienting of attention following assessment of the cued location.

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Table 1.

Mean Accuracy (%) for Motion Discrimination and Probe Localisation Tasks on Valid and Invalid Trials in Experiment 1.

Task	Motion		Probe	
	<i>M (SD)</i>	95% CI	<i>M (SD)</i>	95% CI
Motion cue				
Valid	77.18 (6.59)	[73.79, 80.56]	79.35 (8.75)	[74.85, 83.85]
Invalid	58.18 (14.48)	[50.73, 65.62]	68.88 (10.27)	[63.60, 74.16]
Probe cue				
Valid	70.18 (9.79)	[65.14, 75.21]	81.18 (6.34)	[77.92, 84.43]
Invalid	61.00 (12.11)	[54.77, 67.23]	65.76 (13.93)	[58.60, 72.92]

Note. CI = confidence interval.

Table 2.

Mean Accuracy (%) for Motion Discrimination and Colour Discrimination Tasks on Valid and Invalid Trials for Experiment 2.

Task	Motion		Colour	
	<i>M (SD)</i>	95% CI	<i>M (SD)</i>	95% CI
Motion cue				
Valid	82.58 (6.72)	[79.74, 85.42]	77.63 (9.92)	[73.44, 81.81]
Invalid	70.50 (8.85)	[66.76, 74.24]	73.46 (8.05)	[70.06, 76.86]
Colour cue				
Valid	78.08 (7.43)	[74.95, 81.22]	78.58 (8.17)	[75.14, 82.03]
Invalid	72.33 (8.95)	[68.55, 76.11]	72.71 (9.04)	[68.89, 76.52]

Note. CI = confidence interval.

Table 3.

Mean Accuracy (%) for Motion Discrimination and Colour Discrimination Tasks in Experiment 2, for Trials on Which the Tasks Appeared in the Same Invalid Location or Different Invalid Locations.

Task	Motion		Colour	
	<i>M (SD)</i>	95% CI	<i>M (SD)</i>	95% CI
Motion cue				
Same	73.46 (10.05)	[69.21, 77.70]	75.71 (10.97)	[71.08, 80.34]
Different	69.04 (9.79)	[64.91, 73.18]	72.79 (9.52)	[68.77, 76.81]
Colour cue				
Same	76.83 (9.84)	[72.68, 80.99]	74.96 (8.68)	[71.30, 78.62]
Different	72.25 (10.25)	[67.92, 76.58]	73.38 (9.49)	[69.37, 77.38]

Note. CI = confidence interval.

Figure 1. Procedure for simultaneous motion discrimination and probe localisation task, not to scale. Invalidly cued motion, probe present at cued location. Arrow on target display represents direction of motion and was not displayed. The white dot represents location of the red dot probe. Inset box shows timings during the target display.

Figure 2. Validity effect in the motion discrimination task (grey bars) and the probe localisation task (white bars) in Experiment 1. Error bars represent ± 1 standard error of the mean. The validity effect was calculated by subtracting the percentage accuracy on invalid trials from the percentage accuracy on valid trials.

Figure 3. Validity effect in the motion discrimination task (grey bars) and the colour discrimination task (white bars) in Experiment 2. Error bars represent ± 1 standard error of the mean. The validity effect was calculated by subtracting the percentage accuracy on invalid trials from the percentage accuracy on valid trials.





